iv. Standard Aperture Quadrupoles

The two rings require 276 arc quadrupoles and 144 insertion quadrupoles of standard 8 cm aperture. The magnetic length of the arc quadrupoles is 1.11 m and of the insertion quadrupoles Q4 1.81 m; Q5, Q6, Q8, Q9 1.11 m; Q7 0.93 m.

There are strong economic and technical reasons for maximizing commonality of the designs for all the magnet types; thus the quadrupole is based as much as possible upon the dipole design discussed above. Parameters which have been chosen to be identical are: 1) superconducting cable; 2) operating current; 3) cryogenic design; 4) beam tube; 5) one-layer coil; 6) coil radii; and 7) yoke assembly.

The arc quadrupoles, sextupoles, correctors, and beam position monitors need to be accurately located with respect to the beam and relative to each other. For this reason, they are designed to form one rigid mechanical assembly, as shown in Fig. 1-5. All insertion quadrupoles have a corrector package, and half of the Q9 insertion quads also have a sextupole magnet.

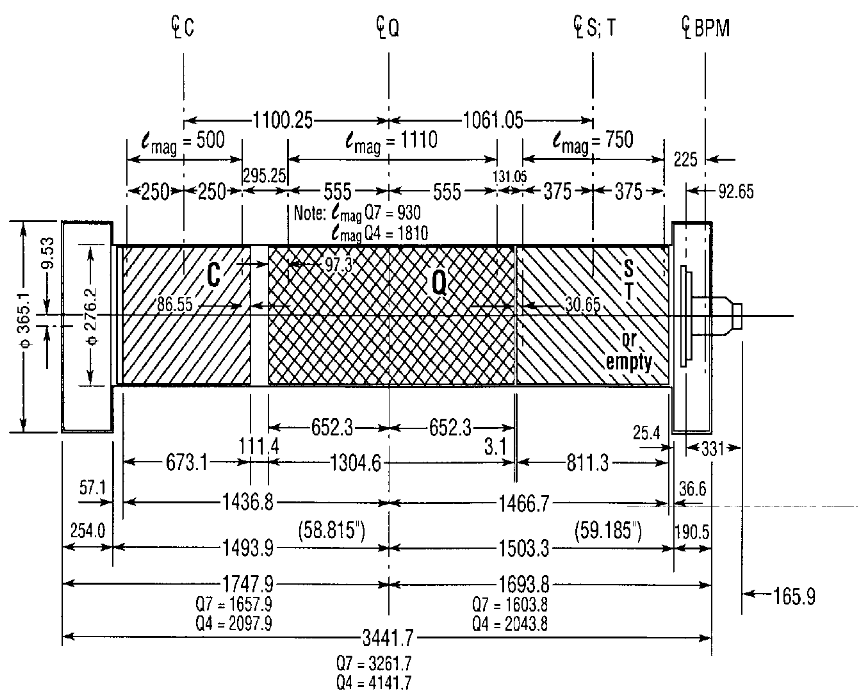

Fig. 1-5. Corrector, quadrupole, sextupole (CQS) assembly. Lamination length is shown (dimensions in mm).

The quadrupole coil design is based on a single-layer "cosine two-theta" coil, wound from a partially keystoned, 30-strand NbTi superconducting cable and mechanically supported by a laminated "cold steel" yoke encased in a cylindrical stainless steel helium containment vessel which is common to the corrector and sextupole. The helium vessel is also a load-bearing part of the yoke assembly. This cold mass assembly is mounted within a cryostat consisting of a cylindrical vacuum vessel, an aluminum heat shield, blankets of multilayer thermal insulation, cryogenic headers, and the magnet support system. Figure 1-6 shows a cross-section of the quadrupole magnet proper or "cold mass." The principal arc quadrupole parameters are given in Table 1-14. The nominal arc gradient requirement is ~71 T/m at top energy, which is obtained with a current of 4.72 kA. The insertion quadrupoles require up to ~6% higher gradients. Larger tuning capabilities are provided by trim quadrupoles at Q4, Q5, Q6.

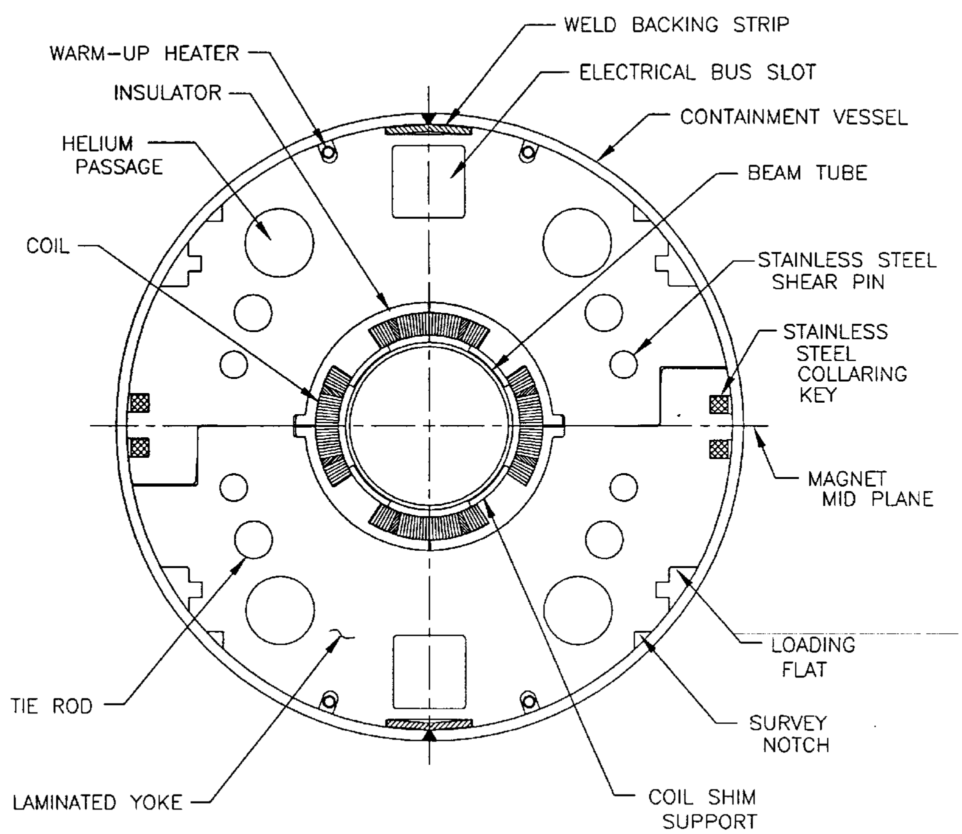

Fig. 1-6. RHIC Arc Quadrupole cross-section (coil i.d. = 79.9 mm).

Table 1-14. Standard Aperture Quadrupole Design Parameters

Coil i.d.	(3.146 in.) 79.9	mm
Coil o.d.	(3.938 in.) 100.0	mm
Number of turns per pole	16	
Number of turns, 1st block (closest to pole)	6	
Number of turns, 2nd block	10	
Wedge angle, bare	13.6	deg
Wedge height, bare	(0.396 in.) 10.06	mm
Effective cable mid-thickness with insulation under compression	(0.05292 in.) 1.344	mm
ARC QUADRUPOLES		
No. quadrupoles, arc	276	
Gradient, @ top energy	~71	T/m
Current, @ top energy	4.72	kA
Gradient, quench	107	T/m
Current, quench	7.65	kA
Magnetic length, arc	1.11	m
Lamination length	(48.4 in.) 1.23	m
Coil length, overall	(48.75 in.) 1.24	m
Coil length, straight section	(39.78 in.) 1.010	m
Cable length per magnet	(504 ft) 154	m
Cable mass per magnet	(27.8 lb) 12.6	kg
Cold mass, CQS package	(2091 lb) 948	kg
Inductance	~2	mH
Stored energy at top energy	20	kJ
INSERTION QUADRUPOLES		
No. quadrupoles, 1.81 m - Q4	24	
0.93 m - Q7	24	
1.11 m - Q5, Q6, Q8, Q9	96	
Gradient @ top energy, Q4, Q5, Q6	75.5	T/m

The quadrupole utilizes a cold stainless steel beam tube of ~69 mm inner diameter. The beam tube design for the CQS package follows the dipoles, except that bumpers are not used because the CQS assembly is straight. The superconducting coil is assembled from quarter-coils that are wound on automated machinery and then formed into a specified size in a precision molding operation - much like the dipole coils. It consists of a single layer of 16 turns per quarter-coil arranged in two blocks with an intervening copper wedge; the size and positions of the wedge and the coil pole spacer have been designed to result in a single-layer coil with field harmonics meeting the rigid field quality specifications required for RHIC. The conductor is the same as that used in the arc dipoles. The cable is insulated with two 50% overlap layers of Kapton film coated with a polyimide adhesive.

The quadrupole yoke design follows directly the dipole design. The yoke laminations are punched from 6.35 mm thick low-carbon steel plate. The lamination surface is phosphate treated. During magnet assembly, a press is utilized to load the coil-in-yoke assembly; it is subsequently held together with stainless steel keys on the outer steel surface to the design preload at room temperature of nominally 69 MPa acting on the coils. After completion, the quadrupole cold mass assembly, together with the sextupole and corrector cold mass assemblies, is inserted snugly into the two halves of a 4.9 mm thick, split stainless steel shell which is then welded along the vertical midplane. The welding operation forms the outer, high-pressure (2.1 MPa) helium containment vessel. This vessel also gives the structure its rigidity and maintains the relative alignment of the component cold masses, which is established by fixturing during the welding operations. This overall assembly is referred to as the CQS cold mass assembly. The CQS assembly is mechanically similar to the dipole assembly, performed with much the same tooling; the principal difference is that the CQS assembly is straight, with no sagitta. The shrinkage of the welds on solidification causes compression of the steel collar blocks, relieving the stress on the keys. Additional compression of the blocks is caused by differential contraction of the stainless steel shell relative to the steel yoke. Since the yoke is completely closed during keying, the coils do not experience any of this increased compressive force.

The design requirements for quadrupole beam tube, yoke, and yoke containment shell are given in Table 1-15.

Table 1-15. Quadrupole Beam Tube, Yoke, and Yoke Containment Shell Parameters

CQS BEAM TUBE		
Outer diameter, bare	(2.875 in.) 73.0	mm
Wall thickness (0.077 in.)	1.96	mm
Weight, nominal	(29 lb) 13.4	kg
Beam tube-coil radial gap	(0.133 in.) 3.4	mm
Magnetic permeability, 300 K	< 1.005	
ARC QUADRUPOLE YOKE		
Inner diameter	(4.300 in.) 109.2	mm
Outer diameter	(10.500 in.) 266.7	mm
Lamination length	(48.4 in.) 1.23	m
Length, including end plates	(51.36 in.) 1.305	m
Lamination thickness	(0.250 in.) 6.35	mm
Length, lamination packs	(0.500 in.) 12.7	mm
Weight of steel	(773 lb) 351	kg
Bus cavity width, height	(1.25 in.) 31.75	mm
Number of cooling channels	4	
Diameter of cooling channels	(1.187 in.) 30.15	mm
YOKE CONTAINMENT SHELL		
Inner diameter (prior to assembly)	(10.516 in.) 267.1	mm
Wall thickness (0.192 in.)	4.9	mm
Weight of common shell for CQS	(215 lb) 97.5	kg
Assembly prestress - Room temperature	(10 kpsi) 69	MPa
- Cold	> (4.8 kpsi) 33	MPa

CQS Cryostat

The cryostat is the structure which must make the transition from the 4 K environment of the magnet cold mass to ambient temperature; the corrector, quadrupole and sextupole (CQS) units are mounted in one common cryostat. In addition, five 50 W "recoolers" per sextant are located under the CQS assembly in the space between the support posts in the 4 K environment. The CQS cryostat design parameters are summarized in Table 1-16. The major components comprising the cryostat are the 6.4 mm thick carbon steel (ASTM A53) vacuum vessel of 610 mm outer diameter, the aluminum heat shield (1100-H14) maintained at nominal 55 K, blankets of multilayer aluminized Mylar thermal insulation, the various cryogenic headers, and the post-type supports which carry the loads generated by the magnet cold masses to the ground. The superinsulation blankets use alternating layers of reflectors (0.25 mil non-crinkled Mylar, aluminized on two sides) and spacers (6 mil REEMAY 2006).

The support posts are the same as used in the arc dipoles. The standard arc CQS assembly is supported by two posts, one located at the sextupole and the other at the corrector. Plans call for them to be precision molded as tubes with flanges from a glass-filled plastic material under the name Ultem 2100. The tubes are in two parts, bolted together at the heat shield. The cold mass is attached to cradles which rest atop each post; the cradles are machined from stainless steel castings. Both cradles are free to move during cooldown; stops on the posts are spaced such that each post is deflected 0.5 mm after cooldown.

The cryostat must accurately position the magnet cold masses to a given point in the accelerator lattice, while at the same time minimizing the refrigeration load. The legs of the vacuum chamber are carbon steel castings. The surfaces of these legs are used to provide the exterior survey fiducial references; survey fixtures will translate the positional information provided by the reference features to a location outside the vacuum tank.

Table 1-16. CQS Cryostat Parameters

Vacuum vessel, outer diameter	(24 in.) 610	mm
Vacuum tank, wall thickness	(0.25 in.) 6.4	mm
Heat shield, outer diameter	(21 in.) 533	mm
Heat shield, wall thickness, upper section	(0.090 in.) 2.29	mm
Heat shield, wall thickness, lower section	(0.125 in) 3.18	mm
Recooler supply header, inner diameter	(2.709 in.) 68.8	mm
Helium return header, inner diameter	(2.709 in.) 68.8	mm
Utility header, inner diameter	(2.709 in.) 68.8	mm
Shield cooling pipe, inner diameter	(2.157 in.) 54.8	mm
Number of supports	2	
Support spacing	(74 in.) 1.88	m
Post, inner diameter	(8.38 in.) 212.8	mm
Post, wall thickness	(0.189 in.) 4.8	mm
Heat leak per leg at 4.5 K	0.1	W
Heat leak per leg at 55 K	1.0	W
Superinsulation layers, cold mass only	17 Reflector, 32 Spacer	
Superinsulation layers, cold mass plus piping	38 Reflector, 53 Spacer	
Superinsulation layers, shield	62 Reflector, 62 Spacer	

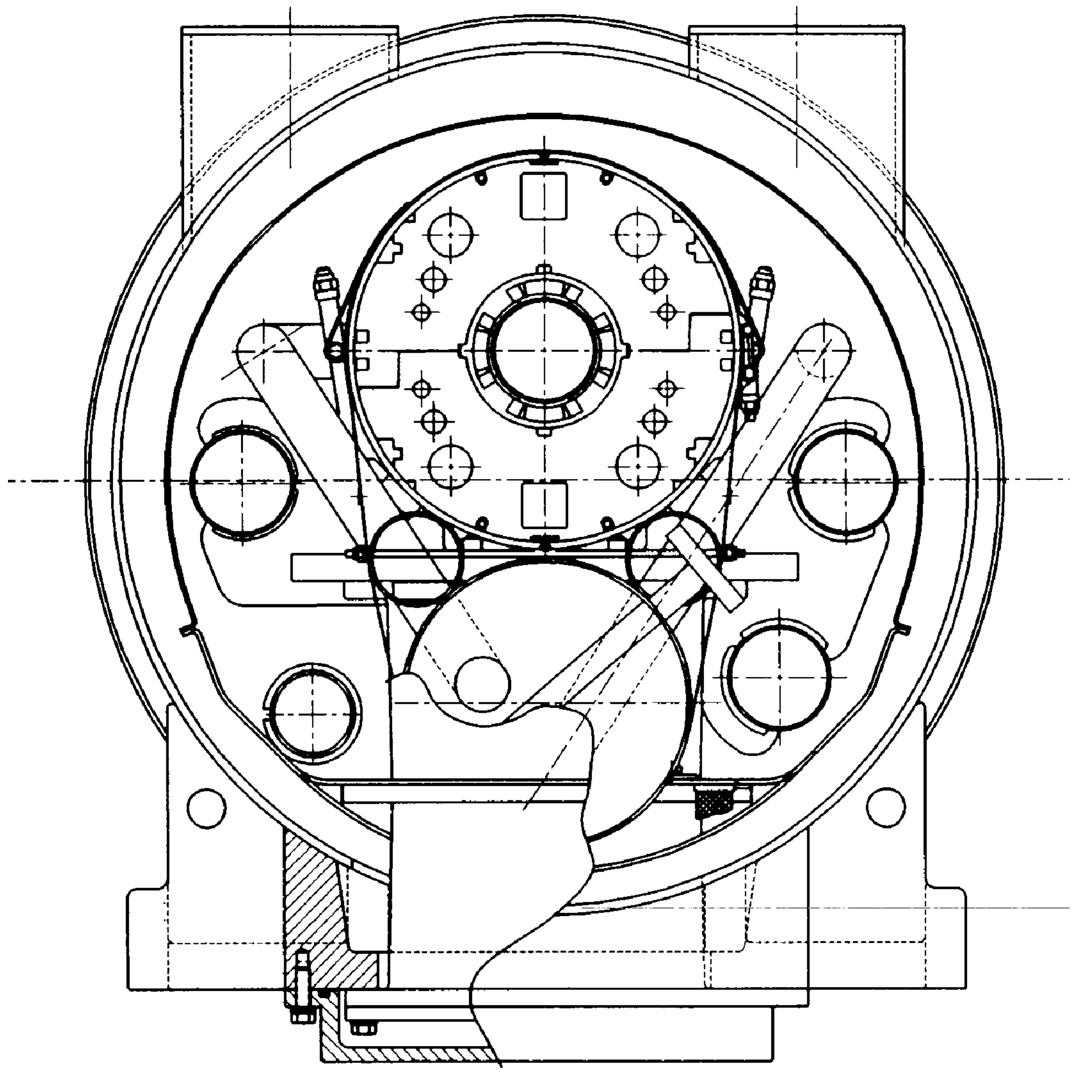

Fig. 1-7. Quadrupole cryostat cross-section, showing recooler.

Table 1-17. Contractual Arc Quadrupole Field Quality Requirements

Tolerance on Integral Field		
Integral quadrupole field, rms		5×10^{-4}
Specified Geometric Field Variations of Measured Multipoles*		
	Allowed Multipoles	
	Systematic (limit)	Random (σ)
Dodecapole, b_5	±1.1	3.4
	Unallowed Multipoles	
	Systematic (limit)	Random (α)
Normal		
Sextupole, b_2	±1.4	4.3
Octupole, b_3	±1.0	2.9
Decapole, b_4	±0.9	2.7
Skew		
Sextupole, a_2	±1.6	4.7
Octupole, a_3	±1.1	3.3
Decapole, a_4	±0.9	2.7
Dodecapole, a_5	±0.2	0.6

*Quoted as 10^{-4} of Quadrupole field at 25 mm radius

Contractually Obligated Arc Quadrupole Magnetic Field Quality

A cold mass that has been properly constructed will have good field quality. Table 1-17 shows the multipole field variations expected in a typical quadrupole cold mass. The number given for each random variation is the maximum standard deviation σ about the mean allowed for any sample of 10 or more consecutively-made magnets. Any particular magnet of a sample may be up to 3 σ outside the listed random variation and still be acceptable, provided the systematic multipoles of the sample remain within the specified value. The integral quadrupole field of the cold mass will be expected to vary from cold mass to cold mass with a variation $\sigma \leq 5\times10^{-4}$. It is anticipated that all cold masses properly built to print will easily pass these field quality tests, and that only a cold mass with serious construction deficiencies will fail to pass the tests.